Security-Based Circuit Breaker Maintenance Management

Payman Dehghanian, Mladen Kezunovic, Gurunath Gurrala, Yufan Guan
Department of Electrical and Computer Engineering
Texas A&M University
College Station, Texas, USA
payman.dehghanian@tamu.edu; kezunov@ee.tamu.edu; ggurrala@ece.tamu.edu; carling@tamu.edu

***Abstract*—Circuit breakers play a vital role in maintaining system security since their malfunctioning could result in further component outages and may lead to the insecure operating conditions. This paper proposes a new approach for identifying the most risky circuit breakers using the condition-based monitoring data and security-based impact evaluations. For a given substation configuration, those circuit breakers which cause line outages due to mal-operation during contacts opening are identified and analyzed. The security oriented risk indices taking into account both voltage violations and overloading conditions as the consequence of circuit breaker mal-operations are proposed. A new breaker maintenance prioritization scheme based on the risk factors is elaborated. The proposed security-based risk framework is deemed to be an efficient approach in both breaker maintenance planning and identification of the breakers which are unreliable for reconfiguration plans. The presented methodology is investigated and verified on the IEEE 14-bus test system.**

***Index Terms*— Circuit breaker; maintenance; monitoring; probability; risk; security.**

NOMENCLATURE

$Con_t(E_i)$	Consequences associated with the outage event *i* at time *t*.
E_i	The i^{th} outage event considered in the risk analysis.
k_1, k_2	Importance factors assigned to the security-based consequence performance indices.
n	Specified exponent used in the system security-based performance indices.
NL	Total number of lines in the system.
NB	Total number of bus-bars in the system.
$Pr_t(E_i)$	Probability of the outage event *i* at time *t*.
$PI_{OL}(E_i)$	System overloading performance index in the post-contingency state of outage event E_i.
$P_l(E_i)$	Power flow of the l^{th} line in the post-contingency state of outage event E_i.
$P_{l,\max}(E_i)$	Maximum possible power flow of l^{th} line in the post-contingency state of outage event E_i.
$PI_{OV}(E_i)$	System overvoltage performance index in the post-contingency state of outage event E_i.
$Pr_{f,t}(C_j^i)$	Failure probability of component C_j in the i^{th} outage event at time *t*.
$Risk_t$	Risk index at time *t*.
$V_j^{\max}, V_j^{\min}$	Maximum and minimum limit voltage magnitudes of the j^{th} bus-bar.
V_j^B	Voltage magnitude of the j^{th} bus-bar in the base case condition of the system under study.
$V_j^{E_i}$	Voltage magnitude of the j^{th} bus-bar in the post-contingency state of outage event E_i.
w_l, w_b	The non-negative weighting coefficients used in system security-based performance indices.
x_{ij}	The reactance associated with the branch connecting bus-bar *i* to bus-bar *j*.
N	Set of the total outage events.
M	Set of components in a certain outage event.
L	Set of the total lines of the system under study.
B	Set of the total bus-bars in the system.

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I. INTRODUCTION

Circuit breakers are deemed to be critical in power system operation since they are used not only for isolating faulted portions of system when faults occur, but also in executing the switching plans aimed at system reconfiguration to meet the required operating constraints. As a result, they have to be readily available and reliable to operate when necessary [1].

Keeping the circuit breakers available is commonly accomplished via the preventive monitoring inspections and maintenance tasks regularly done through asset management policies [2], [3]. Due to the large number of breakers in a system and their different characteristics (age, failure probability, impact of their failure), any decision on their maintenance and the approach to do so may be quite complex. The financial constraints and budget pressure are the other factors which ask for an effective cost differentiation in the maintenance approaches [4]. This has lead to some research conducted on the breaker maintenance and prioritization in the past decade.

Automated monitoring and analysis of circuit breaker operation has been explored in [5]-[7] for need-based maintenance. This approach only helps in utilizing the condition monitoring data for the circuit breakers which may need maintenance but does not associate any criticality measure to the breaker for maintenance prioritization. Critical equipment type identification using some reliability-based indices, e.g., total number of failures, time to repair, energy not delivered within a certain time interval etc., for an effective maintenance scheduling and resource allocation has been proposed in [4]. However, maintaining all the critical breakers may not be an economical solution. Some others have delved into failure probability assessment of circuit breakers via the available monitoring data [8], [9] to get cost/benefit from the breaker monitoring equipment. The authors conducted a component-based and not a system wide analysis to guide an effective maintenance schedule on circuit breakers. A risk framework for maintenance management of circuit breakers using cost-based consequence evaluation and probability measures based on condition monitoring data has been proposed in [10]. This concept of maintenance priority as and when the need arises seems to be economically attractive. But, the cost-based consequences evaluation via the optimal power flow (OPF) analysis becomes computationally intensive for large-scale networks.

The study done in this paper can be regarded as a hybrid component-based (failure probability evaluation) and system wide analysis (failure consequence evaluation), which has been disregarded before, and can be well treated as a response to the nowadays economical concerns and budget constraints among the electric utilities.

The rest of the paper is organized as follows. The concept of risk assessment in power systems is introduced in Section II. The theoretical foundation of the presented approach is discussed in Section III. Section IV demonstrates the paper case study and Section V summarizes the conclusions.

II. Concept of Risk Assessment in Power Systems

Power system risk assessment and management has been widely used at almost all levels of power systems, i.e., generation, transmission, and distribution, in the past decades [11]. Although due to the probabilistic nature of the power system and its associated components, the risk of failure cannot be fully avoided, it can be both evaluated and managed to an acceptable level via the proper planning, designing, operating, and maintenance of the system. Power system risk evaluation commonly incorporates general steps as depicted in Fig. 1. The first step is to determine the system outage states (events). The second step involves determination of outage state probabilities using the failure probabilities of the associated components. The procedure continues with the consequence evaluation of each outage event which can include both technical and economical perspectives. Finally risk indices associated with each outage event can be calculated by the multiplication of the state probabilities with a quantified consequence, as presented:

$$Risk_t = \sum_{i=1}^{n} Pr_t(E_i).Con_t(E_i) \tag{1}$$

In the following Sections, the proposed methodology for the risk analysis of circuit breaker operation based on system security impact assessment is presented and implemented in detail.

III. Security Based Impact Evaluation of Breaker Failures

Each outage event in the power transmission system can be accessed from the impact standpoint where impact is quantified as consequence which may include cost, reliability, security, stability, and vulnerability issues. In this paper, the consequences are treated to be security oriented.

System security is mainly concerned with the successful power system operation in the cases of component outage

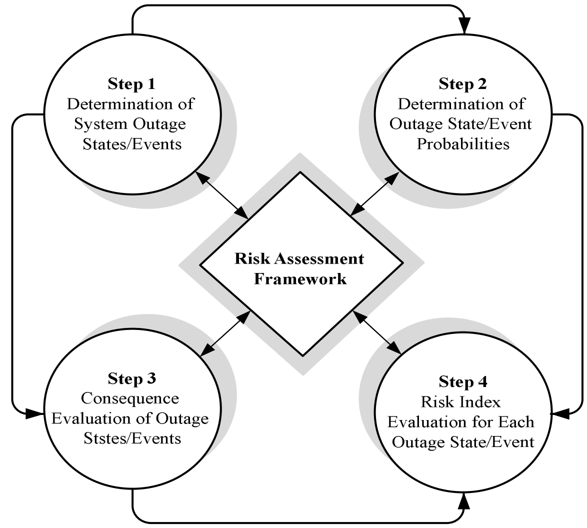

Figure 1. Risk assessment general framework in power system studies.

events. Power system equipment is supposed to be maintained and operated within certain security constraints. Any violation of these limits creates impacts that have to be quantified. In this paper a breaker-and-a-half substation bus configuration is used to demonstrate the concept. In any substation bus-breaker configuration, faults on various components will initiate breaker opening. The faults on various components along with mal-operation of one breaker at a time are considered as events. All the events which lead to line outages are identified. Failure of a breaker itself is also considered as an event. Security assessment due to line outages helps in the detection of any violations in the branch overloading or bus-bar voltages [12].

In considering the imminent overloading conditions in a post-contingency situation, the proposed method utilizes the following performance index of system security.

$$PI_{OL}(E_i) = \sum_{l=1}^{NL} \frac{w_l}{2n} \left(\frac{|P_l(E_i)|}{P_{l,\max}(E_i)}\right)^{2n} \tag{2}$$

$$P_{l,\max}(E_i) = \frac{V_i^{(E_i)} V_j^{(E_i)}}{x_{ij}} \tag{3}$$

This index deals with the post-contingency power flow of the lines compared to the associated maximum possible capacity. Here the post contingency refers to the line outage as a result of corresponding breakers mal-operation. It evaluates the overall overloading condition of the whole system under study [13], [14].

Voltage violations due to any line outage in the system are also treated via (4) which takes into account the system bus-bar voltage magnitudes after the outage in comparison with those of the base case [13], [14].

$$PI_{OV}(E_i) = \sum_{l=1}^{NL} w_b \left(\frac{V_j^{(E_i)} - V_j^B}{V_j^{\max} - V_j^{\min}}\right)^{2n} \tag{4}$$

$$V_j^{\max} - V_j^{\min} = 1.05V_j^B - 0.95V_j^B = 0.1V_j^B \tag{5}$$

The maximum possible deviation allowed for the bus-bar voltage magnitudes is usually considered to be between 95% and 105% of the nominal voltage magnitude. The above-introduced analysis can be done using either type of power flow approaches, e.g. AC power flow and DC or fast decoupled one. It is rather preferred to use the former for the planning purposes and when a decision is to be made with no timing concerns. It is, however, reasonable to have the latter utilized once dealing with an operational decision and when it has to be made as fast as possible.

And finally, the aforementioned performance indices are added up as follows to form the consequence of any breaker mal-operation under consideration.

$$Con_t(E_i) = k_1.PI_{OL}(E_i) + k_2.PI_{OV}(E_i) \quad (6)$$

k_1 and k_2 can be statistically determined using the mean and variance of the numerical index values in various contingencies and n is also supposed to be equal to one in both indices.

For all the identified events consequences are calculated as described above. The event probabilities are calculated using individual component failure probabilities and the breaker probabilities of failure while opening which are obtained as proposed in [10]. As a result, one can easily calculate the risk associated with the events as the multiplication of event probability and consequence. The events can be prioritized based on these risk factors and the circuit breakers involved in the high-ranked events are identified as the most critical ones for priority maintenance.

In order to determine whether breakers are good enough to carry a switching action for reconfiguration, a risk vs. probability of failure chart, as shown in Fig.2, is devised for the entire system. This chart is obtained for the events involving single breaker failures. Those circuit breakers that introduce not only more prominent security-constrained risk outcomes, but also have much higher failure probability are marked in Area 1 of the chart and are indentified as the very critical breakers which are unfit for switching actions. They can be put up for high priority maintenance if they are used frequently for reconfiguration. The circuit breakers lying in the Area 2 are deemed next critical ones as they carry high risk when one performs any switching actions since they have high failure probability. Area 1 & Area 2 circuit breakers have to be taken into account as the constraints to any switching optimization frameworks in the system. Circuit breakers assigned to Area 3 are less critical and can be used for any switching actions bearing in mind that they are assigned a risk more than the threshold level; so they have to be under a certain maintenance consideration to avoid any operation failure and associated risk consequently.

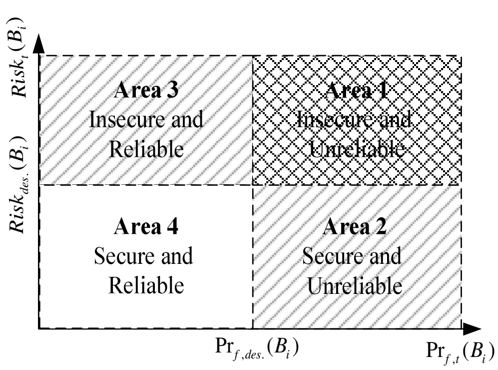

Figure 2. Risk-based decision framework on the identifications of system circuit breaker criticality for maintenance and switching.

The circuit breakers in Area 4 are safe and can be used for any switching actions. They can remain in use longer with the lower frequency of maintenance as well.

The most relevant and promising feature of this approach is that both failure probabilities and outage event risk index due to a circuit breaker malfunction can change dynamically during system operation. As a result, the proposed risk assessment analysis can be performed on-line at regular time intervals to help the maintenance scheduling and switching decision makings.

IV. CASE STUDY

The proposed approach is applied to the bus number 2 of the IEEE 14 bus test system where breaker-and-a-half bus configuration shown in Fig. 3 is used. A generator (G) of 40 MW capacity is connected through breakers 7 and 8 and four transmission lines (L) feed an attached load of 21.7 MW. The associated parameter values and reliability data can be found in [15] and some data is borrowed from [16], [17] as well. The estimated failure probability of circuit breakers via the condition monitoring data at a time and also the other components under study are assumed as presented in Table I.

In order to apply the proposed method, the fault on any single component, which forces the associated breaker opening, is assumed possible. For example fault on bus bar BB1 in Fig. 3 requires opening of breakers B1, B4 & B7. Fault on BB1 and mal-operation of one breaker at a time is considered as an event. All possible events including faults on all the components and failure of breaker itself are listed in Table II. Up to the second order of failures are considered in this study and the switching actions are assumed to be done manually.

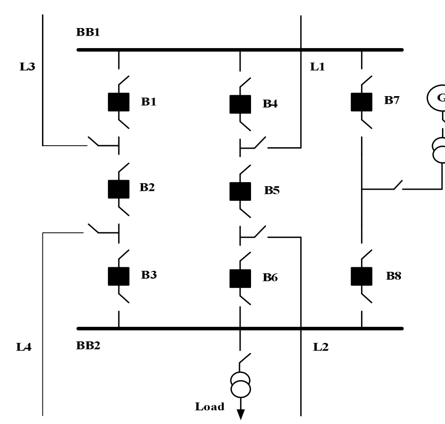

Figure 3. Substation configuration of bus 2 of the IEEE 14-bus Test System.

TABLE I. FAILURE PROBABILITY OF VARIOUS EQUIPMENTS UNDER STUDY [8], [17]

Equipment	Failure Probability
B1, B2, B3, B7, B8	0.4494
B4, B5, B6	0.3909
BB1, BB2	0.0005
G	0.04
L2	0.000477
L3	0.000414
L4	0.000439
L5	0.000427

For the purpose of security-based impact analysis, fast decoupled power flow is used. The coefficients k_1 and k_2 are assumed to be one. The overload and over-voltage based consequences together with the mixed performance index of system security for different outage events are shown in Table II and also Fig. 4. As can be seen, different outage events are directly related to the over voltage or over load consequences. From the viewpoint of security-based impact index, outage events 28, 27, 29, 10 and 11 are determined to have the highest impacts in the system security performance. As a result, the breakers B4, B5 and B2 which are involved in these events, are determined to have the highest consequence and risk. Hence, a prioritization regarding the event risk values can be made and the associated circuit breakers can be planned for more frequent maintenance scheduling with more maintenance resource allocations.

Considering circuit breakers' failure probability, and for the sake of deciding the reliability of the breakers for switching actions, the risk vs. failure probability charts for circuit breakers are constructed as shown in Fig. 5. Here, the results associated with ciruit breakers (events 17, 21, 23, 26, 29, 31, 33, 35) in Table II are concentrated. The desired values of risk and breaker failure probability are assumed to be 0.30 and 0.42, respectively. Circuit breaker 2 has fallen into the Area 1, which means it must not be commanded to operate in a switching plan as it is not only unreliable but also causes huge security impact if it miss-operates. This breaker indicates a need for immediate maintenance if it is to be involved in frequent switching operations for reconfiguration. Circuit breakers 4 and 5 have fallen into the Area 3 which implies that they are reliable enough to be operated for switching; however, if they miss-operate, they will pose a risk higher than allowed or expected. Circuit breaker 6 is the best one for the automated and manual switching purposes. As a result, it has been demonstrated that this risk framework can be updated dynamically since failure probabilities and consequences can be updated via new monitoring data and system topology changes, respectively.

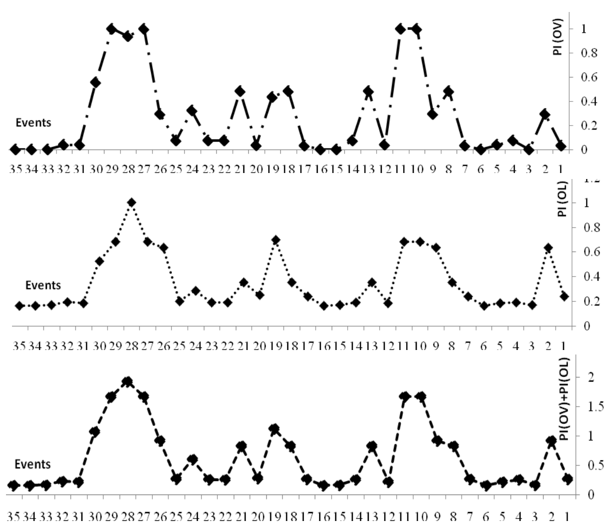

Figure 4. Security constrained consequence results for the considered events.

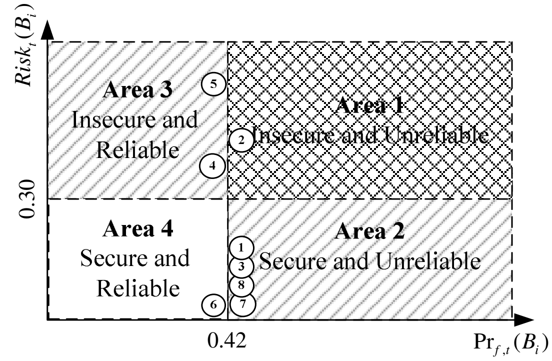

Figure 5. Risk-based decision framework to identify critical circuit breakers.

This dynamic risk assessment may be used for deciding what switching actions to execute as well as what maintenance schedule to assign to circuit breakers. The results can well feed the decision making process of real-time switching actions necessary for the prevention of any possible cascading events or blackouts.

V. Conclusion

To ensure reliable and risk free operation of circuit breakers in a system, maintenance activities have to be well managed and scheduled. However, due to some financial and operational constraints, it seems reasonable to focus more on the critical circuit breakers of the system both for the successful switching and maintenance planning. In this paper, several contributions are made:

- Circuit breaker criticality evaluation has been proposed using a risk based prioritization approach from the system security perspective.
- Security-based consequences causing the over voltage and over loads due to the malfunction of circuit breakers are formulated as a part of the risk analysis.
- The critical circuit breakers to be allocated much more frequent maintenance consideration are defined as those involving the events with the highest security-constrained risk values.
- A risk-based framework to identify the highly reliable and secure circuit breakers for switching policies has been devised.
- The circuit breakers with the maximum failure probability (not reliable) and high outage consequences (not secure) are identified as being critical for a successful switching action and have to be treated as a constraint in the reconfiguration frameworks.
- The proposed risk assessment approach has been applied to circuit breakers of the IEEE 14-bus test system and it has been demonstrated that an effective way of handling the circuit breaker maintenance schedule system-wide is feasible.
- This framework can be used online and may be a significant add-on in scheduling the long or medium-term maintenances on the critical circuit breakers.
- The present approach to identification of critical circuit breakers fits well the nowadays economic concerns and budget constraints in the electric utilities.

TABLE II. SECURITY-CONSTRAINED RISK ANALYSIS OF SUBSTATION CONFIGURATION IN BUS 2 OF IEEE 14-BUS TEST SYSTEM

	Outage Event	Consequences	$PI_{OV}(E_i)$	$PI_{OL}(E_i)$	$Con_t(E_i)$	$Pr_t(E_i)$	$Risk_t(E_i)$
1	BB1, B1	L3 Out	0.032046532	0.240150668	0.2721972	0.000225	6.12444E-05
2	BB1, B4	L1 Out	0.294333635	0.634479093	0.928812728	0.000195	0.000181118
3	BB1, B7	G out	0.000682392	0.171466888	0.172149279	0.000225	3.87336E-05
4	BB2, B3	Load Interrupted and L4 out	0.074957645	0.191455536	0.26641318	0.000225	5.9943E-05
5	BB2, B6	Load Interrupted and L2 out	0.040068951	0.185540232	0.225609183	0.000195	4.39938E-05
6	BB2, B8	Load Interrupted and G out	0.000682392	0.164840744	0.165523135	0.000225	3.72427E-05
7	L3, B1	L3 Out	0.032046532	0.240150668	0.2721972	0.000214	5.82502E-05
8	L3, B2	L3 and L4 Out	0.484177948	0.353968439	0.838146386	0.000214	0.000179363
9	L1, B4	L1 Out	0.294333635	0.634479093	0.928812728	0.000162	0.000150468
10	L1, B5	L1 and L2 Out	1	0.682090289	1.682090289	0.000162	0.000272499
11	L2, B5	L1 and L2 Out	1	0.682090289	1.682090289	0.000172	0.00028932
12	L2, B6	Load Interrupted and L2 out	0.040068951	0.185540232	0.225609183	0.000172	3.88048E-05
13	L4, B2	L3 and L4 Out	0.484177948	0.353968439	0.838146386	0.000192	0.000160924
14	L4, B3	Load Interrupted and L4 out	0.074957645	0.191455536	0.26641318	0.000192	5.11513E-05
15	G, B7	G Out	0.000682392	0.171466888	0.172149279	0.018	0.003098687
16	G, B8	Load Interrupted and G out	0.000682392	0.164840744	0.165523135	0.018	0.002979416
17	B1	L3 Out	0.032046532	0.240150668	0.2721972	0.4494	0.122325422
18	B1, B2	L3 and L4 Out	0.484177948	0.353968439	0.838146386	0.202	0.16930557
19	B1, B4	L3 and L1 Out	0.435172727	0.697822636	1.132995363	0.1757	0.199067285
20	B1, B7	L3 and G Out	0.035114183	0.251904302	0.287018485	0.20196036	0.057966356
21	B2	L3 and L4 Out	0.484177948	0.353968439	0.838146386	0.4494	0.376662986
22	B2, B3	Load Interrupted and L4 out	0.074957645	0.191455536	0.26641318	0.20196036	0.053804902
23	B3	Load Interrupted and L4 out	0.074957645	0.191455536	0.26641318	0.4494	0.119726083
24	B3, B6	Load Interrupted and L2 and L4 out	0.323756324	0.286009865	0.609766188	0.17567046	0.107117907
25	B3, B8	Load Interrupted and L4 and G out	0.074957645	0.200963115	0.275920759	0.20196036	0.055725056
26	B4	L1 Out	0.294333635	0.634479093	0.928812728	0.3909	0.363072896
27	B4, B5	L1 and L2 Out	1	0.682090289	1.682090289	0.15280281	0.257028123
28	B4, B7	L1 and G Out	0.939349291	1	1.939349291	0.17567046	0.340686382
29	B5	L1 and L2 Out	1	0.682090289	1.682090289	0.3909	0.657529094
30	B5, B6	Load Interrupted and L1 and L2 out	0.557303685	0.524586003	1.081889688	0.15280281	0.165315784
31	B6	Load Interrupted and L2 out	0.040068951	0.185540232	0.225609183	0.3909	0.08819063
32	B6, B8	Load Interrupted and L2 and G out	0.040068951	0.194586256	0.234655207	0.17567046	0.041221988
33	B7	G Out	0.000682392	0.171466888	0.172149279	0.4494	0.077363886
34	B7, B8	Load Interrupted and G out	0.000682392	0.164840744	0.165523135	0.20196036	0.033429112
35	B8	Load Interrupted and G out	0.000682392	0.164840744	0.165523135	0.4494	0.074386097

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